

Experimental implications of mirror matter-type dark matter

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Mirror matter-type dark matter is one dark matter candidate which is particularly well motivated from high energy physics. The theoretical motivation and experimental evidence are pedagogically reviewed, with emphasis on the implications of recent orthopositronium experiments, the DAMA/NaI dark matter search, anomalous meteorite events etc.

Keywords: Extensions of the standard model; orthopositronium; dark matter

There is very strong evidence that the Universe has a large non-baryonic dark matter component. On the other hand, the standard model of particle physics does not contain any heavy, stable non-baryonic particles. Clearly, this motivates new particle physics beyond the standard model.

It seems to me that the most interesting candidate for this new physics is mirror symmetry. It is the most interesting candidate because it involves only a single well motivated hypothesis. Parity and time reversal symmetries stand out as the only obvious symmetries which are not respected by the interactions of the known elementary particles. It is an interesting and non-trivial fact that these symmetries can be exact, unbroken symmetries of nature if a set of mirror particles exist. Even more interesting is that the mirror particles have the right broad properties to be identified with the non-baryonic dark matter in the Universe. But we are running ahead of ourselves. Let us start at the beginning...

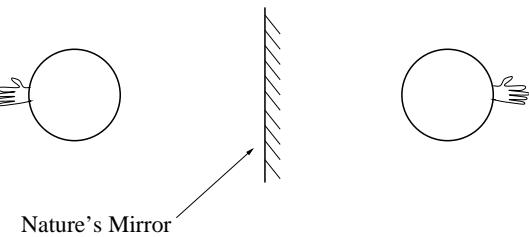
In 1956 Lee and Yang¹ proposed that the interactions of the fundamental particles were not mirror reflection invariant. They suggested that this could explain some known puzzles and proposed some new experiments to directly test the idea. Subsequently Madam C.S.Wu and collaborators dramatically confirmed that the interactions of the known particles were not mirror symmetric, just as Lee and Yang had suspected.

Today, it is widely believed that mirror symmetry is in fact violated in nature. God – it is believed – is left-handed. Actually, though, things are not so clear. What the experiments in 1957 and subsequent experiments have conclusively demonstrated is that the *known* elementary particles behave in a way which is not mirror symmetric. The weak nuclear interaction is the culprit, with the asymmetry being particularly striking for the weakly interacting neutrinos. For example,

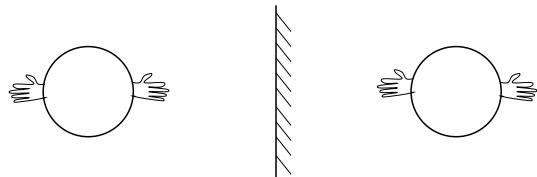
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today we know that neutrinos only spin with one orientation. If one was coming towards you it would be spinning like a left-handed corkscrew. Nobody has ever seen a right-handed neutrino.

The basic geometric point is illustrated in the following diagram:

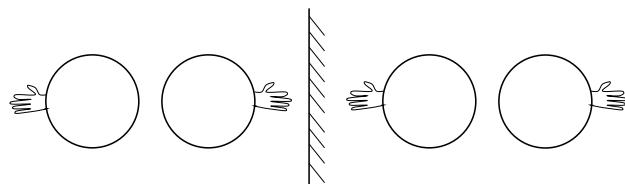


The left-hand side of this figure represents the interactions of the known elementary particles. The forces are mirror symmetric like a perfect sphere, except for the weak interaction, which is represented as a left hand. Also shown is nature's mirror - the vertical line down the middle. Clearly, the reflection is not the same as the original, signifying the fact that the interactions of the *known* particles are not mirror symmetric. If there were a right hand as well as a left hand then mirror symmetry would be unbroken.



However, this doesn't correspond to nature since no right-handed weak interactions are seen in experiments (this is precisely what the experiments in 1957 and subsequently have proven).

There are two remaining possibilities: We can either chop the hand off – but this is too violent and is therefore not shown. It corresponds to having no weak interactions at all, again in disagreement with observations. This last possibility is the most subtle and consists of adding an entire new figure with the hand on the other side. Everything is doubled even the symmetric part, which is clearly mirror symmetric as indicated in the following diagram:



What this figure corresponds to is a complete doubling of the number of particles. For each type of particle, such as electron, proton and photon, there is a mirror twin. Where the ordinary particles favor the left hand, the mirror particles favor the right hand. If such particles exist in nature, then mirror symmetry would be exactly conserved (we denote the mirror particles with a prime).

e		e'
ν		ν'
p		p'
n		n'
\bar{e}		\bar{e}'
$\bar{\nu}$		$\bar{\nu}'$
\bar{p}		\bar{p}'
\bar{n}		\bar{n}'
γ		γ'
w, z		w', z'
G		G'

As will be discussed, the mirror particles can exist without violating any known experiment. Thus, the correct statement is that the experiments in 1957 and subsequently have only shown that the interactions of the *known* particles are not mirror symmetric, they have not demonstrated that mirror symmetry is broken in nature.

The ordinary and mirror particles form parallel sectors each with gauge symmetry G (where $G = G_{SM} \equiv SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ in the simplest case) so that the full gauge group is $G \otimes G$. Mathematically, mirror symmetry has the form:²

$$\begin{aligned} x &\rightarrow -x, \quad t \rightarrow t, \\ W^\mu &\leftrightarrow W'_\mu, \quad B^\mu \leftrightarrow B'_\mu, \quad G^\mu \leftrightarrow G'_\mu \\ \ell_{iL} &\leftrightarrow \gamma_0 \ell'_{iR}, \quad e_{iR} \leftrightarrow \gamma_0 e'_{iL}, \quad q_{iL} \leftrightarrow \gamma_0 q'_{iR}, \quad u_{iR} \leftrightarrow \gamma_0 u'_{iL}, \quad d_{iR} \leftrightarrow \gamma_0 d'_{iL}, \end{aligned} \quad (1)$$

where G^μ, W^μ, B^μ are the standard $G_{SM} \equiv SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge particles, $\ell_{iL}, e_{iR}, q_{iL}, u_{iR}, d_{iR}$ are the standard leptons and quarks ($i = 1, 2, 3$ is the generation index) and the primes denote the mirror particles. There is also a standard Higgs doublet ϕ with a mirror Higgs doublet partner, ϕ' , and it can be shown that $\langle \phi \rangle = \langle \phi' \rangle$ for a large range of parameters of the Higgs potential². This means that the mirror symmetry is *not* spontaneously broken by the vacuum, so that it is an exact, unbroken symmetry of the theory. Interestingly, despite doubling the number of particle types the number of free parameters have not (yet!) been increased: mirror symmetry implies that the masses and couplings of the particles in the mirror sector are exactly the same as the corresponding ones in the ordinary sector.

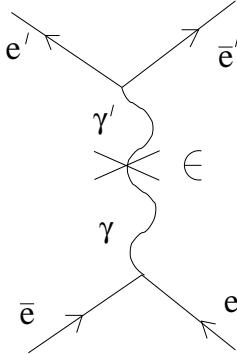
Ordinary and mirror particles couple with each other via gravity and possibly by new interactions connecting ordinary and mirror particles together. Constraints from gauge invariance, mirror symmetry and renormalizability, suggest

only two types of new interactions^{2,a}: a) Higgs-mirror Higgs quartic coupling ($\mathcal{L} = \lambda' \phi'^\dagger \phi' \phi^\dagger \phi$), and b) via photon-mirror photon kinetic mixing: ^b

$$\mathcal{L}_{int} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}. \quad (2)$$

where $F^{\mu\nu}$ ($F'_{\mu\nu}$) is the field strength tensor for electromagnetism (mirror electromagnetism). The effect of the Higgs-mirror Higgs quartic coupling is to modify the properties of the standard Higgs boson^{2,3,8}. This interaction will be tested if/when scalar particles are discovered. The effect of photon-mirror photon kinetic mixing is to cause mirror charged particles to couple to ordinary photons with effective electric charge ϵe ^{2,6,9}.

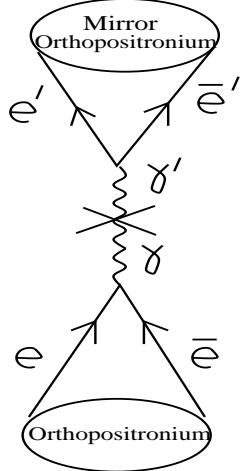
This leads to a number of very interesting effects. In the laboratory, mirror particles can potentially be produced from interactions of ordinary particles: $e^+e^- \rightarrow e'^+e'^-$. The Feynman diagram is given in the following figure:



The best laboratory limits for the production of such light stable “minicharged” particles comes from the SLAC beam dump experiment¹⁰, $|\epsilon| \lesssim 10^{-4}$. However, this is not the most sensitive laboratory test. A more sensitive laboratory test for mirror matter comes from the orthopositronium system¹¹. The interaction of e^+e^- with $e'^+e'^-$ leads to a small mass term mixing orthopositronium with mirror orthopositronium. The Feynman diagram is given in the following figure.

^aAllowing the ordinary and mirror sectors to interact with each other leads to two new free parameters (λ' , ϵ). However, compared to other ideas beyond the standard model, many of which have literally hundreds of new parameters, mirror symmetry *is* a fairly minimal extension of the standard model. Also note, if the neutrinos have mass, mass mixing between ordinary and mirror neutrinos is also possible^{3,4} and might be implicated by the observed atmospheric, solar and LSND neutrino anomalies. However, the experimental situation is still not clear⁵.

^bTechnically, the photon-mirror photon kinetic mixing arises from kinetic mixing of $U(1)_Y, U(1)'_Y$ gauge bosons, since only for abelian $U(1)$ symmetry is the mixing term, FF' , gauge invariant. Therefore there is both $\gamma - \gamma'$ and $Z - Z'$ kinetic mixing. [However, experiments are much more sensitive to $\gamma - \gamma'$ kinetic mixing which is why we focus attention on it]. In the case of theories without $U(1)$ gauge symmetries, such as GUTs, the $\gamma - \gamma'$ mixing can arise radiatively⁶. Interestingly, there is a class of models where ϵ vanishes at one and two loop level⁷, and therefore naturally of the order of $\epsilon \sim 10^{-8}$.



The effect of this mass mixing term is to cause orthopositronium to (maximally) oscillate into mirror orthopositronium:

$$P(O \rightarrow O') = \sin^2 \omega t, \quad (3)$$

where $\omega = \pi \epsilon f$, where $f = 8.7 \times 10^4$ MHz is the contribution to the ortho-para splitting from the one photon annihilation diagram involving orthopositronium.

In an experiment, mirror orthopositronium decays are not detected, which means that the number of orthopositronium, N , satisfies¹¹

$$N = \cos^2 \omega t e^{-\Gamma^{SM} t} \approx \exp[-t(\Gamma^{SM} + \omega^2 t)] \quad (4)$$

where $\Gamma^{SM} \simeq 7.03998 \mu s^{-1}$ is the standard model orthopositronium decay rate¹². Evidently, the observational effect of the oscillations is to increase the apparent decay rate of ordinary orthopositronium: $\Gamma^{eff} \approx \Gamma^{SM} + \omega^2 / \Gamma^{SM}$. In practice, orthopositronium is not produced in vacuum, but undergoes elastic collisions at a rate, Γ_{coll} , which depends on the particular experiment. These collisions cause decoherence, disrupting the oscillations. In the limit $\Gamma_{coll} \rightarrow \infty$, the mirror world effect goes to zero¹³. In all of the existing experiments, the collision rate exceeds the orthopositronium decay rate, which means that the apparent decay rate is given by¹⁴:

$$\Gamma^{eff} \approx \Gamma^{SM} \left(1 + \frac{2\omega^2}{\Gamma^{SM} \Gamma_{coll}} \right). \quad (5)$$

The 1990 vacuum cavity experiment performed by a team at the University of Michigan¹⁵ showed a small but statistically significant excess (about 0.1%), which suggested¹⁴ an $|\epsilon| \approx 10^{-6}$. However, a new vacuum cavity experiment¹⁶, also performed by the Michigan group, finds no anomaly:

$$\Gamma^{exp} / \Gamma^{SM} = 1.00006 \pm 0.00018. \quad (6)$$

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In the 2003 experiment, the orthopositronium typically makes two wall collisions per lifetime, which is comparable to the 1990 Michigan experiment. The net effect is a 2σ upper limit on the value of ϵ of:

$$\frac{2\omega^2}{\Gamma_{SM}\Gamma_{coll}} < 0.00042 \Rightarrow |\epsilon| < 5 \times 10^{-7}. \quad (7)$$

Orthopositronium experiments can also directly search for invisible decay modes. This can be done by tagging the positrons and searching for events with missing energy¹⁷. This would essentially be a mirror orthopositronium ‘appearance’ experiment (rather than a ‘disappearance’ experiment, which is what you get from orthopositronium lifetime studies). With that technique the sensitivity to photon-mirror photon kinetic mixing can be greatly enhanced - if the experiment is done in vacuum. This would be very important because such an experiment (already planned¹⁸) could potentially probe ϵ values down to 10^{-8} and possibly even lower. This would be very useful because there are interesting indications for ϵ of order 10^{-8} coming from the DAMA/NaI dark matter experiment¹⁹, as we will now discuss.

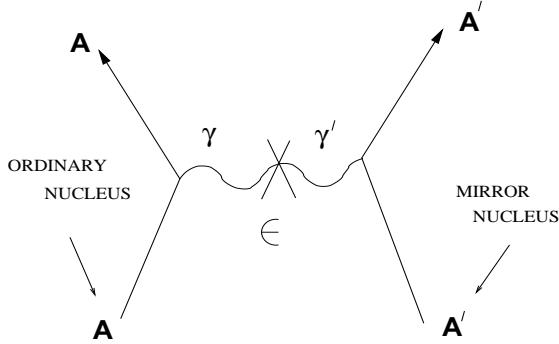
If mirror matter is identified with the dark matter in the Universe, then it is natural to interpret the dark matter halo of our galaxy as containing mirror stars/planets/dust and gas.^c. In fact, viewed from afar, by a mirror observer, our galaxy may well resemble an elliptical galaxy – the ordinary matter in the disk would be invisible of course. The important point is that if the dark matter halo of our galaxy is composed of mirror matter, then galactic mirror atoms and dust particles can potentially be detected in dark matter experiments via the nuclear recoil signature²²

The reason is that the photon-mirror photon kinetic mixing interaction, Eq.(2), gives the mirror nucleus, with (mirror) atomic number Z' , a small effective ordinary electric charge of $\epsilon Z'e$. This means that ordinary and mirror nuclei can elastically scatter off each other (essentially Rutherford scattering). For a mirror atom of mass $M_{A'}$ and (mirror) atomic number Z' scattering on an ordinary target atom of mass M_A and atomic number Z , the cross section is given by:

$$\frac{d\sigma}{dE_R} = \frac{\lambda}{E_R^2 v^2}, \quad (8)$$

where $\lambda \equiv 2\pi\epsilon^2\alpha^2Z^2Z'^2/M_A$. In this equation, v is the velocity of the mirror nucleus in the lab frame (i.e. where the ordinary nucleus is at rest) E_R is the recoil energy of the ordinary nucleus. The basic Feynman diagram for this process is given in the following figure:

^c According to the MACHO gravitational microlensing study²⁰, the proportion of halo dark matter in our galaxy in compact form is in the range 8 – 50% (95% C.L.). These compact halo objects can be interpreted as mirror stars, mirror white dwarfs etc²¹, with the remaining portion of the halo ($\gtrsim 50\%$) in the form of gas and dust.



The experiment with the most data is the DAMA/NaI experiment¹⁹. The aim of the DAMA/NaI experiment is to measure the nuclear recoils of Na, I atoms due to the interactions of dark matter particles. This interaction rate should experience a small annual modulation due to the Earth's motion around the sun:

$$A \cos 2\pi(t - t_0)/T. \quad (9)$$

According to the DAMA analysis¹⁹, they indeed find such a modulation over 7 annual cycles at more than 6σ C.L. Their data fit gives $T = (1.00 \pm 0.01)$ year and $t_0 = 144 \pm 22$, consistent with the expected values. [The expected value for t_0 is 152 (2 June), where the Earth's velocity, v_E , reaches a maximum with respect to the galaxy]. The strength of their signal is $A = (0.020 \pm 0.003)$ cpd/kg/keV [cpd \equiv counts per day].

These are extremely impressive results which demand serious consideration. No systematic uncertainty which can mimic this effect has been identified and it therefore seems probable that DAMA has discovered dark matter. Interestingly the interpretation of the DAMA/NaI signal in terms of standard WIMPs appears to be disfavoured by a number of experiments^{23,24}. However, if we interpret the DAMA/NaI signal in terms of mirror matter-type dark matter then the conflict with the other experiments is alleviated²².

In the case of a halo composed of H' , He' , heavier mirror elements and dust particles, there are important differences to the standard WIMP case due to mirror particle self interactions. For example, assuming a number density of $n_{He'} \sim 0.08 \text{ cm}^{-3}$ (which is suggested if He' makes a significant contribution to the halo dark matter) the mean distance between $He' - He'$ collisions is $1/(n_{He'} \sigma_{\text{elastic}}) \sim 0.03$ light years (using $\sigma_{\text{elastic}} \sim 3 \times 10^{-16} \text{ cm}^2$). One effect of the self interactions is to locally thermally equilibrate the mirror particles in the halo. The He' (and other mirror particles) should be well described by a Maxwellian velocity distribution with no cutoff velocity. [He' do not escape from the halo because of their self interactions]. A temperature, T , common to all the mirror particles in the halo can be defined, where $T = M_{A'} v_0^2 / 2$ (of course, T will depend on the spatial position). One effect of this is that v_0 should depend on $M_{A'}$ with $v_0(A') = v_0(He') \sqrt{M_{He'}/M_{A'}}$. Thus, knowledge of v_0 for He' will fix v_0 for the other elements. It is natural to set

Experiment/Target	$v_{min} (H')$	$v_{min} (He')$	$v_{min} (O')$	$v_{min} (Fe')$
CRESST ²⁶ / Al_2O_3	(Al) 913 km/s	252 km/s	88 km/s	48 km/s
	(O) 720 km/s	212 km/s	85 km/s	54 km/s
DAMA/NaI ¹⁹	(Na) 2834 km/s	795 km/s	290 km/s	167 km/s
	(I) 11656 km/s	2982 km/s	813 km/s	298 km/s
CDMS/Ge ²³	5992 km/s	1559 km/s	450 km/s	186 km/s
Zeplin I/Xe ²⁴	7980 km/s	2040 km/s	555 km/s	201 km/s

$v_0(He') \sim 230$ km/s (the sun's velocity relative to the galactic center) if the matter density of the galactic halo is dominated by He' (as hinted by BBN²⁵).

In an experiment such as DAMA/NaI, the measured quantity is the recoil energy, E_R , of a target atom. The minimum velocity of a mirror atom of mass $M_{A'}$ impacting on a target atom of mass M_A is related to E_R via the kinematic relation:

$$v_{min} = \sqrt{\frac{(M_A + M_{A'})^2 E_R}{2M_A M_{A'}^2}}. \quad (10)$$

Values for v_{min} for impacting mirror H' , He' , O' , Fe' (which span the range of interest), for various experiments are given in the above table. As the table shows, the experiments most sensitive to mirror elements are DAMA/NaI and CRESST/Sapphire, because the other experiments have $v_{min} \gg v_0(A')$. Furthermore, DAMA is mainly sensitive to O' , Fe' and fairly insensitive to H' , He' . CRESST on the other hand is sensitive to He' , O' and Fe' (but the CRESST experiment has much less data than the DAMA experiment).

The interaction rate of halo dark matter with a detector depends on the Earth's velocity relative to the halo. Because of the Earth's annual motion, its velocity satisfies:

$$\begin{aligned} v_E(t) &= v_\odot + v_\oplus \cos \gamma \cos \omega(t - t_0) \\ &= v_\odot + \Delta v_E \cos \omega(t - t_0) \end{aligned} \quad (11)$$

where $v_\odot \approx 230$ km/s is the Sun's velocity with respect to the galactic halo and $v_\oplus \simeq 30$ km/s is the Earth's orbital velocity around the Sun (and $\omega = 2\pi/T$, with $T = 1$ year). The inclination of the Earth's orbital plane relative to the galactic plane is $\gamma = 60^\circ$, which means that $\Delta v_E \approx 15$ km/s. The event rate in an experiment will thus contain an annual modulation term:

$$R_i = R_i^0 + R_i^1 \cos \omega(t - t_0) \quad (12)$$

where

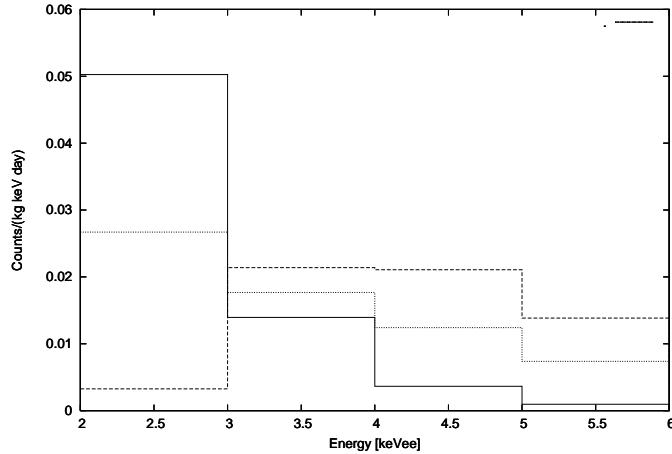
$$\begin{aligned} R_i^0 &= \frac{1}{\Delta E} \int_{E_i}^{E_i + \Delta E} \left(\frac{dR}{dE_R} \right)_{v_E=v_\odot} dE_R \\ R_i^1 &\simeq \frac{1}{\Delta E} \int_{E_i}^{E_i + \Delta E} \frac{\partial}{\partial v_E} \left(\frac{dR}{dE_R} \right)_{v_E=v_\odot} \Delta v_E dE_R. \end{aligned} \quad (13)$$

The DAMA/NaI collaboration have found such an annual modulation for the 2-6 keV energy range: $R^1(2 - 6\text{keV}) = 0.020 \pm 0.003 \text{ cpd/kg/keV}$.

The DAMA/NaI experiment is not very sensitive to light mirror elements H' and He' . The reason is the relatively high value for v_{min} (see the earlier table). However, the DAMA/NaI experiment is quite sensitive to any O' and/or Fe' component. Interpreting the DAMA experiment in terms of mirror O' , Fe' mixture, the annual modulation effect in the 2-6 keV window can be explained if²²:

$$|\epsilon| \sqrt{\frac{\xi_{O'}}{0.10} + \frac{\xi_{Fe'}}{0.02}} \simeq 4.5 \times 10^{-9} \quad (14)$$

where $\xi_{A'} \equiv \rho_{A'}/(0.3 \text{ GeV/cm}^3)$ is the A' proportion (by mass) of the halo dark matter. The relative contribution of O' and Fe' can in principle be determined by the detailed differential spectrum in keV bins rather than using the 4 keV window (2-6 keV). This is illustrated in the figure below. In this figure the solid line is $\xi_{O'} = 0.10$, $\xi_{Fe'} \ll 0.02$, the dashed line is $\xi_{Fe'} = 0.02$, $\xi_{O'} \ll 0.10$, and the dotted line is a 50-50 mixture, $\xi_{O'} = 0.05$, $\xi_{Fe'} = 0.01$. [$\epsilon = 4.5 \times 10^{-9}$ in each case].



This interpretation appears to be consistent with other experiments, in contrast to the standard WIMP interpretation of the DAMA/NaI signal.

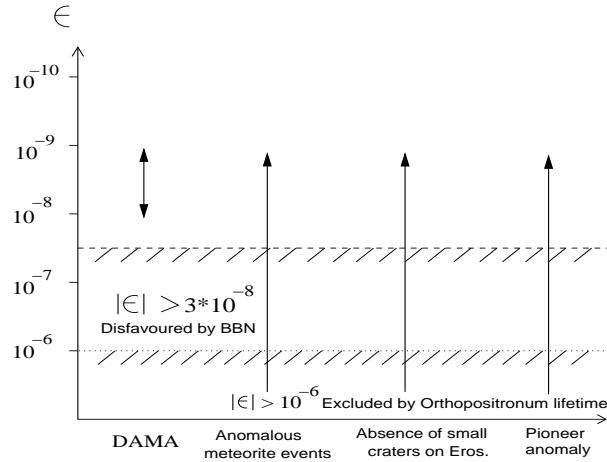
Of course there are many other implications of mirror matter-type dark matter. Perhaps the most fascinating possibility is that our solar system contains mirror matter space-bodies^{27,28}. Collisions of such bodies with themselves and ordinary bodies would generate a population of dust particles and larger bodies which could impact with the Earth. The impact velocity must be in the range:

$$11 \text{ km/s} \lesssim v \lesssim 70 \text{ km/s} \quad (15)$$

Small dust particles could be detectable in simple surface experiments. In particular, experiments such as the St. Petersburg experiment²⁹ are sensitive to solar system

mirror dust particles³⁰. Such particles can produce a burst of bremsstrahlung photons upon passing through ordinary matter. These photons can be detected via a PM tube, and the velocity of the mirror dust particle thereby determined. Ordinary cosmic rays should be travelling close to the speed of light, and can thereby be distinguished from relatively slow moving mirror dust particles. The St. Petersburg experiment finds a positive signal corresponding to a flux of about 1 mirror dust particle per square meter per day.

Impacts of larger bodies should be less frequent, nevertheless there is a fascinating range of evidence for their existence. The largest recorded impact event was the 1908 Tunguska event. Remarkably no asteroid or cometary remnants were recovered from the Tunguska site³¹. People have *assumed* that the impacting body was made of ordinary matter, however there is no solid evidence to support this claim. The Tunguska body may have been made out of dark matter – which is a logical possibility if mirror matter is identified with the dark matter of the Universe. In fact, this hypothesis seems to provide a better explanation for the known features of the Tunguska event²⁸. There are also many other ‘anomalous’ impact events, on smaller scales³³, and evidence for anomalous impact events on larger scales³⁴ which seem to be explicable if interpreted as mirror matter impacts. Other solar system evidence for mirror matter also exists coming from the lack of small craters on the asteroid EROS^{35,36} and also from the anomalous slow-down of *both* Pioneer spacecraft^{37,38}. This overall situation is summarized in the figure below:



Finally, let us mention that another large impact event has occurred recently in Siberia, devastating about 100 square kilometers of forest³² (c.f. ~ 2100 square kilometers in the 1908 Tunguska event³¹). Preliminary searches have not found any meteorite fragments, despite the existence of a large number of small craters at the site³². If this impact event is due to a (pure) mirror matter body, it should not have slowed down as rapidly in the atmosphere as an ordinary matter body (for $\epsilon \sim 10^{-8} - 10^{-9}$ as suggested by DAMA/NaI results, the air molecules typically

pass through the body losing only a relatively small fraction of their momentum³⁶). This might be testable from satellite observations of the bolide (which are obviously unavailable for the 1908 Tunguska event, but should be available for this recent Siberian event)^d. Direct detection of mirror matter fragments in the ground is also possible at these impact sites. The photon-mirror photon kinetic mixing interaction can lead to a small static force which can keep small mirror matter fragments near the Earth's surface³⁹. Such fragments can be experimentally detected via the centrifuge technique³⁹ and through the thermal effects of the embedded mirror matter on the surrounding ordinary matter⁴⁰.

In conclusion, mirror matter-type dark matter is a well motivated alternative to standard WIMP dark matter. In fact, mirror matter-type dark matter seems to be theoretically preferred since it requires only a single hypothesis - mirror symmetry of fundamental interactions. In comparison, the preferred WIMP models require at least three *independent* hypothesis a) low energy supersymmetry b) the lightest susy particle (LSP) is neutral and c) R-parity exists (to keep the LSP thing stable). Of course, the important point is that experiments can in principle test the mirror matter dark matter hypothesis, and there is currently (> 6 sigma!) evidence from the DAMA/NaI experiment, along with a set of other, independent, observations which seem to support the mirror matter-type dark matter hypothesis.

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^dOf course, it is also possible that the body could have a small amount of ordinary matter embedded within it which would make it 'opaque' to air molecules. However, even in this case there will be important differences due to the rate of ablation of the body: For an ordinary matter body, the surface heats up rapidly and is continuously melting thereby reducing the size of the body. In the mirror matter case, the heat is spread out within the entire volume of the body (not just on the surface), which means that the rate of ablation is much lower than in the ordinary matter case. Since smaller bodies decelerate more quickly than larger bodies, the reduced ablation rate for impacting mirror matter objects will imply a reduced rate of deceleration in the atmosphere.

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